

Chapter 4

Techno-Economic Development of WECs

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4.1 Introduction

4.1.1 Continuous Evaluation of the WEC Potential

The development of a WEC, from having a good idea to demonstrating a commercially viable WEC, is an exciting but challenging journey. If the technology is right, it is expected to take about 15 years and a cost of two-digit million euros (in the best case) [1]. However, most of the technologies that are being developed will most likely never reach commercialisation, because they are not capable of producing market competitive electricity or they do not manage getting the required funding to proceed with development.

In order to avoid wasting large amounts of resources into the development of a technology, its potential of producing electricity at market price needs to be assessed continuously. Whenever the resulting LCoE calculation at the end of a development phase concludes that it is not sufficient for successful commercialisation, then there is little reason to proceed with its development. The chance that the further development of the technology will lower the LCoE is very small, while chances are rather high that unexpected cost will occur and, thereby, the final LCoE will be higher. If this unpleasant situation should occur, the fundamentals of the technology have to be readdressed, bringing the development of the technology back to the research phases [2].

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The calculation of the actual LCoE from a commercially operated WEC power plant relies on many assumptions and estimations. As long as a full-scale WEC has not been operated at the location of interest for a sufficient amount of time, there will be uncertainty in the power production and in the related costs. These uncertainties are larger, the further the technology is from commercialisation. So, throughout the development of a WEC, it is one of the main objectives to tackle these uncertainties. The further the development proceeds, the smaller these uncertainties will become and, thereby, a better estimation of the actual LCoE can be made. Various tools and calculations sheets are publicly available, which can facilitate the calculation of the LCoE [3–5].

4.1.2 Overview of the Techno-Economic Development

The technical performance level (TPL) and technical readiness level (TRL) scales, which are presented in Sect. 4.3.1, are especially used to rate the technical maturity (TRL) and economic potential (TPL) of a new technology and are very convenient as they facilitate the comparison between different developing technologies, even outside the wave energy sector. However, in practice a WEC is usually developed following a more specific set of development stages. These technical development phases of WECs are explained more in detail in Sect. 4.2 and can be coupled to the TRL scale [6].

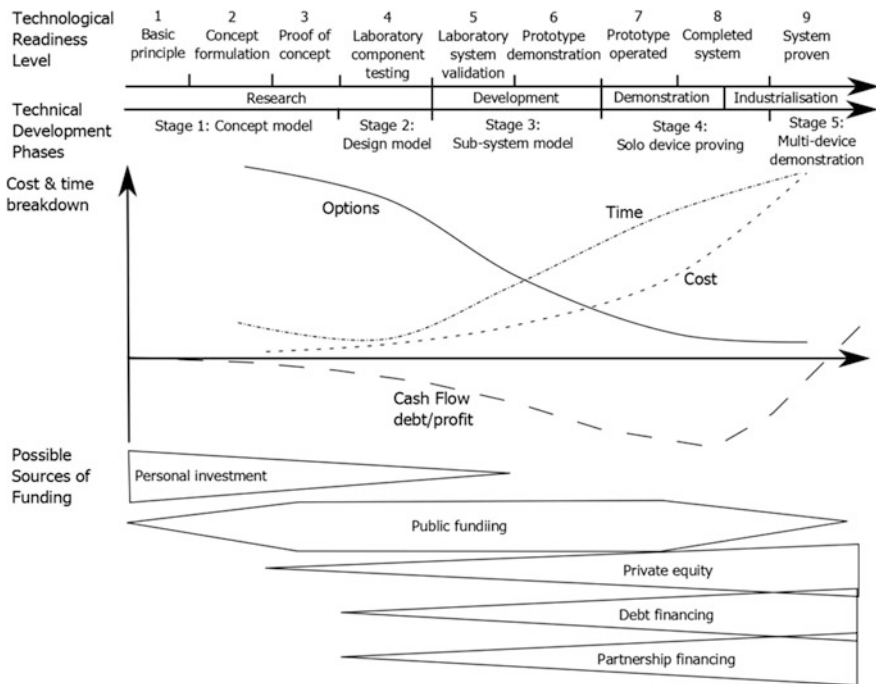


Fig. 4.1 Overview of different techno-economic parameters and how they typically evolve during the technical development of a WEC [1, 7–9]

Figure 4.1 presents an overview of how the time, cost and design parameters evolve with the technical development phases and, thereby, also the TRL. The main trends are that the required time and expenses increase significantly with increasing TRL while the amount of design variables that can be changed decrease significantly. The sources of funding usually tend to change significantly throughout the development process as well.

As no technology has yet been successfully commercialised, the current “best practice” is still based on experiences from other sectors and on assumptions from experts in the wave energy sector. Thereby, the details in the Fig. 4.1 remain approximate.

Note that the development strategy, which can be strongly influenced by the financing body, has a significant influence on the cost and time break-down over the different development stages. Some might favour spending additional time at the research level where all options are still open and time and cost are relatively small, only to proceed when a sufficient LCoE level (TPL) has been reached. Other financing bodies might favour a faster (but more risky) development process in which the TRL prevails. Some different possible development strategies are discussed in Sect. 4.4.4.






4.2 The WEC Development Stages

The technical development of a WEC can generally be divided into 5 main development stages [10]. Each stage is characterised by very specific goals and objectives which make it possible to progress systematically. As the development of WECs is very time-consuming and capital intensive, it is a challenge to keep these to a minimum. However, proceeding too quickly in a phase or even missing a phase can and will most likely have significant negative repercussions on the further development of the WEC. Note that modifications to the concept or design of the WEC should be done as early as possible through the development as this will become only more difficult, costly and time-consuming if they are done at a later stage.

The following Table 4.1 presents the different development stages that characterise a typical development path of WECs, from idea to commercialisation. It includes the main characteristics of each of them. Note that:

- Each development stage requires specific WEC model(s)/prototype(s) that will be subjected to specific challenges and objectives.
- From development phase 3, no significant changes to the overall WEC configuration are supposed to be made, thereby proceeding from the research to the development.
- The power production outcomes from laboratory tests should rely on tests in representative wave conditions for locations of interest.
- At the end of each phase, the progress and LCoE have to be evaluated. Based on this, a decision is made on whether the development can be taken to the next phase or if it is even worth continuing the development of the WEC.

Table 4.1 Detailed overview of the five development stages for wave energy converters [7, 9, 11]

	Stage 1: Concept model	Stage 2: Design model	Stage 3: Functional model	Stage 4: WEC prototype	Stage 5: Array demonstration
Illustration					
Scale	1:20–1:100	1:10–1:50	1:3–1:10	1:1–1:3	1:1
Location	Laboratory	Laboratory	Laboratory/benign site	Open seas	Open seas
Model/Prototype characteristics	<ul style="list-style-type: none">– Idealized setup– Load-adaptable PTO– Adaptable design variables	<ul style="list-style-type: none">– Final design– Representative characteristics– Simulated PTO	<ul style="list-style-type: none">– Full fabrication– True PTO and Electrical generator	First fully operational device	Autonomous and operational WEC power plant
Waves	Representative power production and extreme sea states	Representative power production and extreme sea states	Pilot site waves	Operational and extreme sea states	Operational and extreme sea states
Experimental test objectives	<p>Main</p> <ul style="list-style-type: none">– Concept validation and optimisation– Power performance estimation– Assessing the impact of design variables and environmental parameters <p>Possibly also</p> <ul style="list-style-type: none">– PTO and mooring char.– Loads estimation– Movement estimation (RAO's)	<p>Main</p> <ul style="list-style-type: none">– Power performance estimation– Mooring and structural loads– Sea keeping– PTO conditions– Assessing the impact of design and environmental variables <p>Possibly also</p> <ul style="list-style-type: none">– Detailed numerical calc.– Feasibility study	<p>Providing experimental data and experience on</p> <ul style="list-style-type: none">– Power performance– Wave-to-wire model, including control strategy– Mooring and structural loads– Survival and sea keeping– Marine environment	<p>Real cost and power production data for projection for device sales</p> <ul style="list-style-type: none">– CapEx– OpEx– Energy production <p>And also</p> <ul style="list-style-type: none">– Wave-to-wire model– Structural and mooring forces– Lifecycle assessment	<p>Real cost and power production data for projection for WEC array sales:</p> <ul style="list-style-type: none">– Array CapEx– Array OpEx– Array Energy production <p>And also for WEC array</p> <ul style="list-style-type: none">– Wave-to-wire model– Structural and mooring forces– Lifecycle assessment
Techno-economic development of WECs					

4.3 Techno-Economic Development Evaluation

4.3.1 The Technology Readiness and Performance Level

Recent work to provide ways of measuring the progress and the value of technology R&D processes has focused on adapting the TRL to specific wave energy terms and the introduction of a new TPL scale.

ESBI and Vattenfall [12] have prepared the wave energy TRL scale focusing on functional readiness and lifecycle readiness. While, Weber [1, 13] has prepared the TPL scale focusing on an all-round performance assessment with heavy emphasis on innovation and assessing economic viability. Additional wave farm TRL scales have been published [14] and a complimentary scale of Commercial Readiness Levels (CRL) has been defined to extend beyond the R&D phase [15].

Functional readiness means the readiness to convert ocean wave energy and export it to grid in addition to other related and essential functions such as station keeping and remote monitoring. The TRL scale gives indications of how these should be demonstrated at different TRL levels. Lifecycle readiness means readiness in non-functional areas that are important to utilities; these include operational readiness, supply chain readiness, risk reduction and also cost estimation and reduction. Inherent to the TRL scale is a focus on certification and a related expectation for the end user to be required to insure against certain risks (Table 4.2).

Table 4.2 The technological readiness levels (TRL)

TRL	Functional readiness	Lifecycle readiness
9	Operational performance and reliability demonstrated for an array of WECs	Fully de-risked business plan for utility scale deployment of arrays
8	Actual full-scale WEC completed and qualified through test and demonstration. (1:1 Froude)	Actual marine operations completed and qualified through test and demonstration
7	WEC prototype demonstration in an operational environment. (>1:2 Froude)	Ocean operational readiness: management of ocean scale risks, marine operations, etc
6	WEC prototype demonstration in a relevant environment. (>1:4 Froude)	Customer interaction: consider customer requirements to inform design. Inform customer of likely project site constraints
5	WEC component and/or basic WEC subsystem validation in a relevant environment. (>1:15 Froude)	Supply-chain mobilisation: Procurement of subsystem design, installation feasibility studies, cost estimations, etc
4	WEC component and/or basic WEC subsystem validation in a laboratory environment. (>1:25 Froude)	Preliminary lifecycle design: targets for manufacturable, deployable, operable and maintainable technology
3	Analytical and experimental critical function and/or characteristic proof-of concept	Initial capital cost and power production estimates/targets established
2	WEC concept formulated	Market and purpose of technology identified
1	Basic principles observed and reported	Potential uses of technology identified

The TPL scale is focused on performance as a combination of social, environmental and legal acceptability, power absorption and conversion, system availability, capital expenditure (CapEx) and operational expenditure (OpEx). Inherent to the TPL scale is a focus on Cost of Energy (CoE) and on improving this through innovation at low TRL. A further focus of the TPL is on formulation and automation of the performance assessments. An important component of the performance assessment is techno-economic simulation and optimisation; this ideally combines simulation of the physical processes in wave energy absorption with operational simulation, financial assessment and numerical optimisation techniques [16–18] (Table 4.3).

Table 3.4 The technological performance levels (TPL)

TPL	Category	Performance
9	High: Technology is economically viable and competitive as a renewable energy form	Competitive with other energy sources without special support mechanism
8		Competitive with other energy sources given sustainable support mechanism
7		Competitive with other renewable energy sources given favourable support mechanism
6	Medium: Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological and/or conceptual improvements required	Majority of key performance characteristics and cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions
5		In order to achieve economic viability under distinctive and favourable market and operational conditions, some key technology implementation improvements are required
4		In order to achieve economic viability under distinctive and favourable market and operational conditions, some key technology implementation and fundamental conceptual improvements are required
3	Low: Technology is not economically viable	Minority of key performance characteristics and cost drivers do not satisfy potential economic viability
2		Some of key performance characteristics and cost drivers do not satisfy potential economic viability
1		Majority of key performance characteristics and cost drivers do not satisfy and present a barrier to potential economic viability

4.3.2 The WEC Development Stages and the TRL Scale

The five technical development stages (see Sect. 4.2) are specific to the wave energy sector while the TRL scale, which rates the technical maturity (see Sect. 4.3.1), is widely used in other industries.

Although these two systems are in some aspects very different, they can still be combined and compared as they both follow the development of a new product. This is presented in the following Table 4.4.

Table 4.4 The TRL and WEC development stages [12, 19]

WEC development phase	TRL	Short description	Model/prototype	Required funding	System fundamentals flexibility
1	1	Basic principles observed and reported	Scaled models or subsystems in relevant environment	+	+++++
	2	Technology concept and/or application formulated			
	3	Analytical and experimental critical function and/or characteristic proof-of-concept			
2	4	Technology component and/or basic technology subsystem validation in a laboratory environment	Scaled prototype to full-scale WEC in sea trials	++	++
3	5	Technology component and/or basic technology subsystem validation in a relevant environment			
	6	Technology system model or prototype demonstration in a relevant environment			
4	7	Technology system prototype demonstration in an operational environment		++++	+
4–5	8	Actual technology system completed and qualified through test and demonstration			
5	9	Operational performance and reliability of an array demonstrated	WEC array	+++++	+

4.3.3 The TRL-TPL R&D Matrix

As mentioned before, The TPL scale (from 1 to 9) presents the economic potential of a WEC while the TRL scale (from 1 to 9) presents the technical maturity level of a technology. These two evaluation scales can be combined in the TRL-TPL matrix, also called the Weber R&D matrix. This TRL-TPL matrix allows the status of a wave energy technology R&D programme to be represented as a point on the TRL-TPL plane and the history of the R&D progress up to that point as well as projections of future progress to be charted as lines.

A TRL-TPL matrix is presented in Fig. 4.2, in which the horizontal axis of the diagram is the TRL and the vertical axis is the TPL.

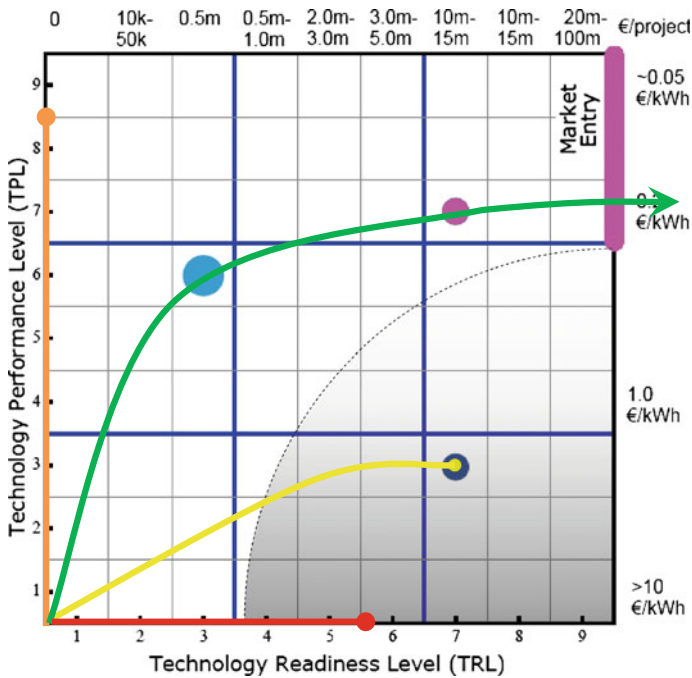


Fig. 4.2 Weber R&D Matrix. *Top edge* gives indicative spend. *Right edge* gives indicative performance levels. All R&D starts at *bottom left*. *Purple bar* is “market entry” the R&D goal. *Purple dot* is minimum viable product. *Green line* is an effective performance-before-readiness R&D trajectory. *Shaded area* is a “graveyard” for R&D programmes with low TPL. Adapted from [12] with permission

The right edge of the matrix is marked with indicative LCoE, which represents the TPL. Higher TPL levels are associated with more competitive cost of energy.

The top edge of the matrix is marked with indicative R&D spend or “burn rate”. Higher TRL levels are associated with higher capital “burn rates” as the R&D expenditures and the project risks also increase dramatically with the TRL.

All technology developments enter the process at the left of the diagram and, if all goes well, proceed along a rightward and upward trajectory towards market entry. Successful market entry requires a fully developed WEC (TRL 9) that is commercially viable, meaning a TPL between 7 and 9 (with or without financial support).

The grey area represents the “graveyard”. This area indicates the TRL-TPL combinations at which further developments should probably be ceased as it is very unlikely that from that point on the product will ever become economically viable. If the developer would, however, decide to proceed with the development, significant changes will have to be made to the basics of the concept, thereby returning to an earlier TRL in the hope to raise the TPL (see Sect. 4.4).

During the technical development of the WEC—in the form of experimental tests, numerical models and analysis—design decisions are made concerning the fundamentals of the concept. These WEC fundamentals are numerous and very flexible at an early stage as everything is still open for discussion while they are being addressed and, thereby, being fixed together with the development. Thereby, it is of great importance not to fix fundamental parameters of the WEC as long as the TPL is not at least 7 or above. Figure 4.3 presents the different domains of the TRL-TPL matrix.

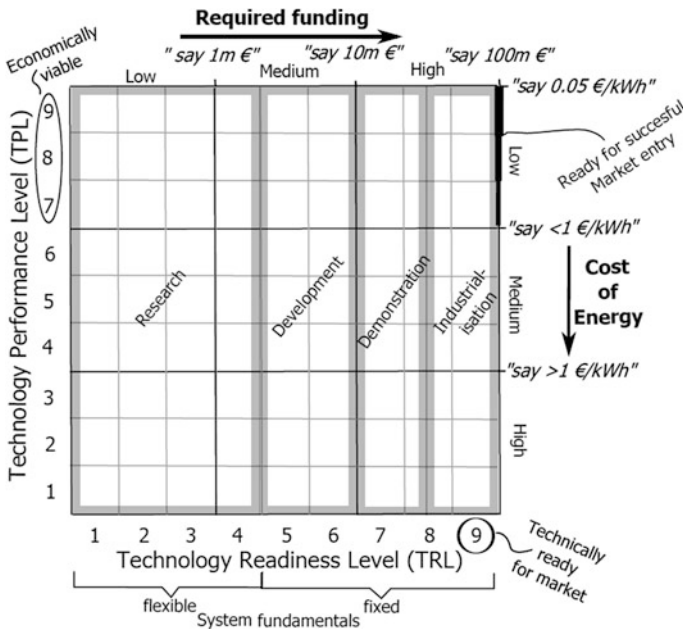


Fig. 4.3 Overview of the TPL-TRL matrix with related information [1]

While system fundamentals are flexible (left half of the diagram), the primary R&D goal should be to increase TPL with an emphasis on analysis, innovation and assessment of many alternatives and where this is facilitated by low cost and low risk activities. After a concept with sufficiently high TPL has been identified, the system fundamentals should be fixed and the R&D should progress to the right-hand side of the Weber diagram. In the right half of the diagram, the primary R&D goal is to increase TRL; in this domain the emphasis is on demonstration and risk reduction. In the right-hand domain, innovation must be much more cautiously managed to reduce risk in large projects and must be limited to improving sub-systems. Ideas for entire system improvements must be tested at lower TRL and treated as new projects.

4.3.4 *Uncertainty Related to the TRL-TPL Matrix*

As stipulated before, the LCoE for a commercially-operated power plant, based on a particular WEC, should be estimated at the end of each development stage. During the development of a WEC, the numerous assumptions and unknowns related to the cost and power production are addressed systematically. Thereby, the uncertainty related to the LCoE, which is a function of the cost and power production of a WEC, gets gradually reduced with the development phases. Table 4.5 presents EPRI attempt to quantify the level of uncertainty related to the estimated cost based on the technology’s design maturity.

Table 4.5 Cost estimate rating table showing cost uncertainty as a percentage [20]

Design maturity \\calculation detail	1. Conceptual (idea or lab)	2. Pilot	3. Demonstration	4. Commercial	5. Mature
A. Actual	–	–	–	–	0
B. Detailed	–	–	–15 to +20	–10 to +10	–5 to +5
C. Preliminary	–30 to +50	–25 to +30	–20 to +20	–15 to +15	–10 to +10
D. Simplified	–30 to +80	–30 to +30	–25 to +30	–20 to +20	–15 to +15
E. Goal	–30 to +200	–30 to +100	–30 to +80	–30 to +70	–

The values in the Table 4.5 are unlikely to be generally applicable. However, they give a probable indication of the uncertainty linked to the estimated cost of a WEC project. The overall uncertainty related to a WEC project will even be greater as there is also a fair level of uncertainty linked to the power production, which depends on the environmental conditions and availability of the WECs.

Figure 4.4 gives an example of possible LCoE estimations that have been re-evaluated all along the technical development of a WEC. The optimistic and pessimistic LCoE estimations illustrate the uncertainty related to the mean LCoE estimation.

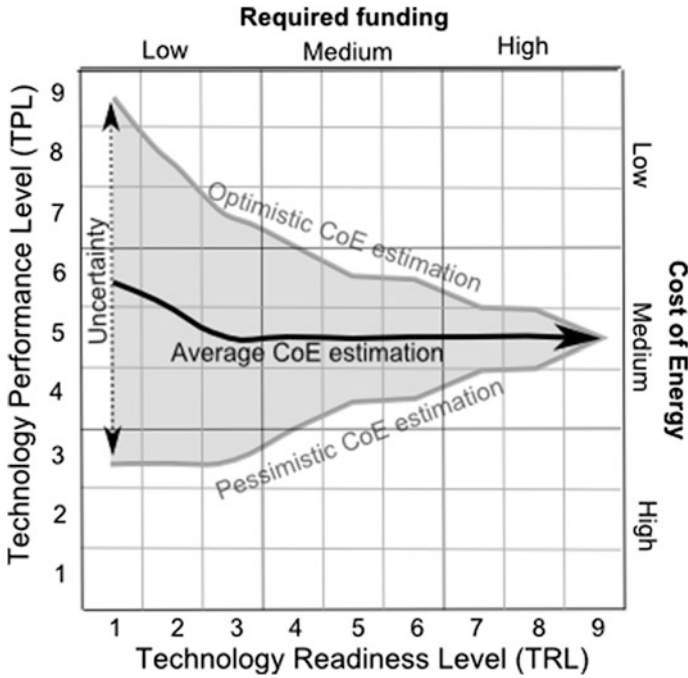


Fig. 4.4 Possible progress of the CoE estimation (TPL) with the technology development (TRL), together with an illustration of the potentially related uncertainty

The average LCoE estimation is the average between the optimistic and pessimistic LCoE estimation. Besides the uncertainty on the estimation, a different result might be obtained depending on who makes the calculation (e.g. developer or independent third-party). It is unfortunately difficult to estimate the fully correct LCoE in any case before a commercially operated power plant based on a particular WEC is built and operated over its full lifetime. So, it is of great importance that the LCoE estimation is transparent where (possible) assumptions are disclosed.

4.3.5 Valuation of R&D Companies

A further use of the Weber R&D matrix is as a guide for assessing the technology companies which are half-way through an R&D programme. For example, consider the different R&D programmes represented by a TRL = 7 and TPL = 3 and another case with a TRL = 3 and TPL = 6 (see dots in Fig. 4.2); imagine that the companies conducting these R&D programmes are raising equity. Which is more investible?

Conventional wisdom might argue that the higher TRL programme is closer to market readiness and, therefore, that the additional investment needed to bring the R&D to completion is less than in the case of the lower TRL programme. If an

assessment is done purely on the basis of the TRL, then the dark blue dot would appear to represent the more advanced R&D programme. However, as already established in the previous sub-section, this programme is likely to stall or at least to have to go back to the drawing board: it finds itself in the “R&D graveyard”. Conversely, the light blue dot, although at a lower TRL, is at a much higher TPL and crucially is much closer to the green trajectory. A valid relative measure of an R&D programme is, therefore, how close it is to a trajectory that will result in successful (affordable) market entry.

4.4 Techno-Economic Development Strategies

4.4.1 *R&D Strategy as TRL-TPL Trajectories*

An R&D manager has to choose the allocation of resources between achieving readiness before performance or performance before readiness. A readiness-before-performance trajectory would involve progressing along the TRL scale first and then along the TPL scale, so an R&D programme would have to complete multiple design iterations at high TRL and high cost and would be consequently unlikely to succeed. The horizontal red line represents an extreme version of this trajectory while the yellow line represents a less extreme version. It is possible for such development efforts to achieve a midlevel TRL, using a combination of private funding and public grant support. However, at higher TRLs the increased cost of R&D attracts greater levels of due diligence and such an effort would stall due to low TPL estimates in due diligence. The lower right area of the matrix is a “graveyard” for R&D programmes that rush through the early TRL stages too quickly and do not focus on achieving a high TPL while still at low TRL and low cost of design iteration. The orange and green lines are performance-before-readiness trajectories. The vertical orange line represents a trajectory that corresponds to a pure thought experiment; a WEC concept that never leaves the log book or imagination of the inventor. In principle, it is possible for this trajectory to reach high TPL, but with very high uncertainty in the TPL since no physical testing is done. This trajectory is not practical because it remains at very low TRL for too long; testing at TRL 2 & TRL 3 is needed to reduce uncertainty in the assessments in the early stages of the R&D effort. The green line represents a more practical version of the performance-before-readiness trajectory.

A trap to be avoided is attempting readiness before performance strategy in the belief that performance can be increased after market entry in line with anticipated learning rates. This strategy can be successful only in cases where (i) initial investment is sufficient to reach market entry and (ii) the product is viable so that customers buy multiple generations, and learning rates can come into consideration. In wave energy, neither of these conditions are likely to occur. A readiness before performance strategy is almost certain to fail in reaching market entry while a

performance before readiness strategy will deliver a viable product more cheaply than any other strategy.

Weber [13] argues that the rapid increase in TPL is made possible by structured innovation techniques such as TRIZ [21] and techno-economic optimisation [22] applied at low TRL. A key requirement to success in this stage is flexibility in concept definition. The performance-before-readiness strategy facilitates this because radical changes to system fundamentals—e.g. from a point absorber to a terminator or from a submerged to a surface piercing device—are affordable and manageable at lower TRL. Conversely, at high TRL such changes would be prohibitively expensive, risky and would actually violate several guidelines for WEC development [23–25]. A consequence of the focus on flexibility and concept level innovation is that it may be necessary to test several or even many concepts to TRL 2 or TRL 3 in order to choose between alternatives for further development. A challenge in implementing the performance-before-readiness development trajectory is related to dealing with uncertainties in understanding the characteristics of the mature system before that system is actually available. This translates into a requirement for sophisticated techno-economic assessment and optimisation software for judicious use of experimental testing and, most importantly, for a structured approach to the innovation.

4.4.2 Extreme Cases of Techno-Economic Development Strategy

The techno-economic development strategy for a WEC might differ with respect to the importance of TPL or TRLs. Some extreme cases of techno-economic development strategies could favour one of them radically above the other [1], meaning that the WEC developer would prioritise:

- A rapid technology development of the WEC without addressing the technology performance. Here, the WEC developer will try to minimise the duration between the (initial) development phases. This strategy will be referred to as “Readiness before Performance”.
- The performance of the WEC needing to be optimised before proceeding to the next development phase. Here, no progress in terms of development stage is made as long as the highest TPL, where no subsidies are required, is proven to be within reach. This will be referred to as “Performance before Readiness”.

The adopted development strategy is usually a result of the different opinions and agendas of the different stakeholders behind the WEC, e.g. the inventor, (public and/or private) funding body etc., which might favour one strategy over the other. Table 4.6 presents an overview of the particularities of these two strategies.

Table 4.6 Overview of two extreme techno-economic development strategies

Readiness before performance	Performance before readiness
<i>Characteristics</i>	
<ul style="list-style-type: none">– The WEC developer favours a quick development of the WEC, to limit the time spent at each TRL– The TPL is assumed to be sufficient, based on optimistic CoE estimations or on secondary importance– It is believed that the WEC fundamentals can be improved at a later stage, which is in practice very difficult, costly and time-consuming, and prior experience can become obsolete	<ul style="list-style-type: none">– The WEC developer favours a thorough technical development of the WEC– At each TRL, the TPL is enhanced to optimal level, which is very time consuming and work intensive. However, when/if TRL 9 is reached the WEC is directly ready for successful market entry– The extensive work at each TRL also reduces the related uncertainty as all aspects have been carefully investigated
<i>Possible argumentation</i>	
<ul style="list-style-type: none">– Being satisfied with its initial TPL, arguing it does not require any further development– Trying to rapidly become an important player in the sector– Trying to gain time (at early TRLs) believing it will also limit the related financial means– It is easier to attract interest (and funding) when the technical development is fast and the models/prototypes are larger	<ul style="list-style-type: none">– Believing that the TPL is the most important, as there is no point to further develop a WEC that will not be competitive with other energy sources, without special support mechanism– That from the moment the highest TPL is reached, the rest (interest from investors etc.) will follow

TRL_TPL matrix illustration

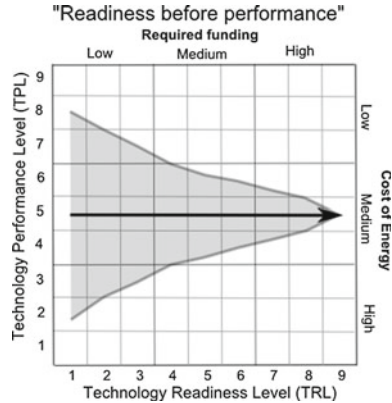


Fig. 4.5 Illustrates the readiness before performance development strategy

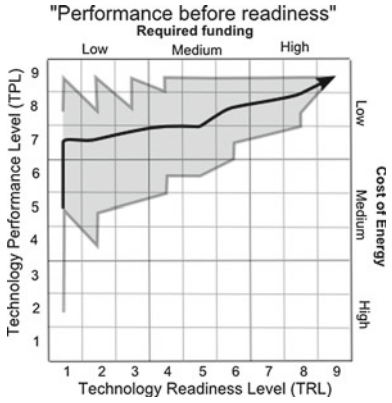


Fig. 4.6 Illustrates the performance before readiness development strategy

(continued)

Table 4.6 (continued)

Readiness before performance	Performance before readiness
<i>(Probable) development pathway</i>	
<ul style="list-style-type: none"> – The (first) development phases are passed rapidly, a lot of physical progress can be shown – At some point, it becomes relatively difficult to attract more funding, as the TPL does not justify the further development – Significant technical modifications are required to proceed with the development and in order to argue that the technology can become economically-viable – Here for, earlier development phases need to be repeated, requiring new designs, models and prototypes – This will be very expensive, time-consuming and making previous experience possibly obsolete. Moreover, the new design might still not lead to a commercially viable technology if the new fundamentals are not right 	<ul style="list-style-type: none"> – The first development phases take a lot of time and effort as every aspect of the technology is carefully investigated – It might be difficult to get public attention, as progress is slow, models are small (at least during the first development stages) and the system might seem more complicated, as many more details have been investigated – It might be difficult to bridge the gap to sea trials; however, the value of the technology should become very clear the further it gets with the technical development – Once the technology can be demonstrated offshore in a reasonable size, most of the uncertainties should fade away and the commercial and technical potential should be clear – In case the technology, during its development, shows that it is not capable to reach TPL 9, then the technical development will be stopped and unnecessary time and cost will be avoided

In both cases, it can take a very long time to arrive at the required TPL and TRL to reach a successful market entry. For the “Readiness before Performance”, the whole development will need to be repeated with updated WEC fundamentals while the “Performance before Readiness” will require substantial amounts of funding if the development duration becomes really long. The next sub-chapter will present a middle road.

4.4.3 *Efficient Techno-Economic Development*

First of all, the fundamentals of the WEC need to allow the technology to become commercially viable. This is of major importance and needs to be obvious and presentable at the end of each development phase. This might be a bit more difficult at early development phases as uncertainties are larger, but it should be well documented before sea trials take place. Therefore, all important aspects of the WEC technology, such as mooring, structural design, power production, survival mechanism, PTO design and others need to be assessed carefully in representative wave conditions before the WEC technology goes to sea trials.

Assuming that the fundamentals of the WEC in development are capable of bringing the WEC to a successful market entry, then the development trajectory should be optimised in order to limit the required amount of funding and the overall time to market. As changes to the WEC fundamentals are still flexible, relatively cheap and fast to change at early development stages, this should be the first priority. A lot of effort at relatively low cost can be dedicated in the beginning, e.g. optimising the Wave-to-Wire (W2W) performance and minimising the structural requirement, which can lead to substantial LCoE improvements. This will, in practice, mean various experimental test campaigns, using various models of the full system and of sub-systems separately so that the influence of a large range of physical and environmental parameters can be assessed. This will lead to an optimised design and an extensive knowledge of the loads and design characteristics of all essential parts of the device. The parallel development of a W2W numerical model can be highly valuable if it can be sufficiently accurate.

Figure 4.7 illustrates this efficient performance-before-readiness techno-economic development strategy.

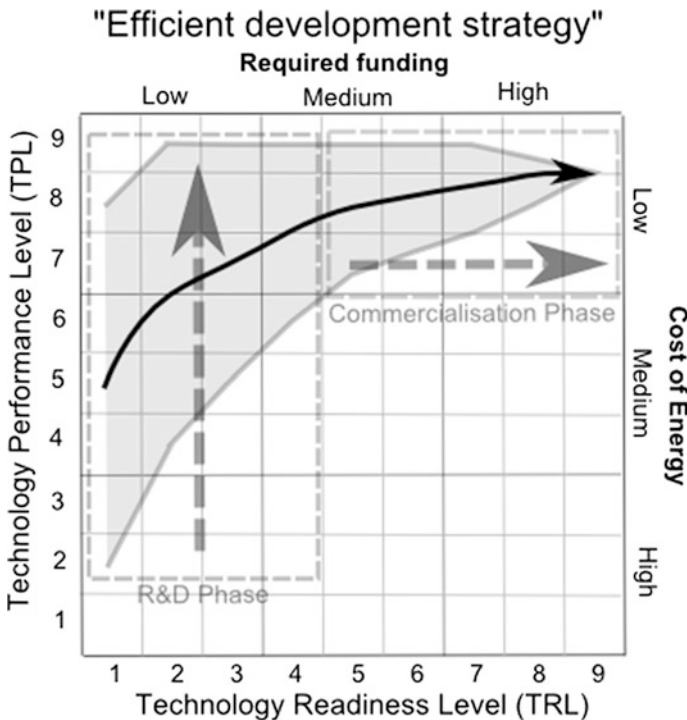


Fig. 4.7 Illustration of a possible successful and efficient techno-economic development of a WEC

Once the early development phases (mainly research) have maximised the TPL, the focus should be put on reducing the time to market in order to secure WEC sales income rather than further relying on external funding. This will be the start of the development process, which aims at demonstrating the WEC operating in a real sea environment. The first prototype will be of a reduced scale and operating in a benign site where the WEC can operate in reasonable wave conditions. The aim will be to have it be fully-functional and operating as an autonomous power plant unit. It should, however, also present storm condition data so that the storm configuration of the WEC can be assessed and extreme loads on the structure be measured. The last development stage will then present a full-scale WEC that is able to operate fully autonomously and that is ready for successful market entry. There will always be room for improvements, and they will have to be addressed in parallel with the commercial activities of the WEC company as any technology-based company do.

4.5 Conclusion

The successful development process of WECs demand large amounts of time and means. The optimal development trajectory manages to keep these expenses to a minimum while delivering an economically viable product at the end of its development. As related expenses (time and money) increase exponentially with the development stages (TRLs) while flexible parameters decrease rapidly, it is of the highest importance to optimise the WEC principles at an early stage (TRL 1-4) up to the level where the economic potential of the WEC is ensured ($TPL > 7$).

If, when passing TRL 4 (working principles of the WEC are fixed and the new outlook is demonstration), the TPL is not greater than 7 (at least economic viable with incentives), then the subsequent expenses will be wasted and could possibly harm the credibility and/or image of the technology developer or even the sector. In general, during each TRL of the development, the potential of the WEC of being capable of achieving successful market entry ($TPL > 7$) has to be assessed, taking the uncertainty with this estimation into account. If this turns out to be negative or indicates doubts relative to its potential, then the progress in terms of TRL should be stopped and it might even be required to go some development steps back. This will be the only option, as significant modifications to the WEC fundamentals are only possible at early TRLs.

When looking at the WECs currently being developed internationally, the working principles of WECs are still very broad (see Chap. 2) while only a very small fraction of these are expected to be able to reach the satisfactory TPL for successful market entry. These WECs in development have often rushed too quickly into the TRLs as they have produced too optimistic estimations of their TPLs (or they did not take the importance of the TPLs seriously).

4.6 Overview of Some of the Leading WECs

Table 4.7 presents an overview of some of the leading WEC technologies. These are indicative numbers shared by the corresponding companies at some point in the past. More WEC technologies could have been added, such as Wavestar, AW energy’s Waveroller, AWS, Fred Olsen, Weptos, Seabased and possibly many others.

Table 4.7 Overview of some key figures of the development of WEC [26–35]

Company/model	OPD Pelamis	Aquamarine Oyster	OPT PowerBuoy	Oceanlinx	Carnegie CETO
Development start (year)	1998	2001	1994	1997	1999
Duration to first approx. full-scale prototype	6 years (2004)	7 years (2008)	11 years (2005)	9 years (2006)	11 years (2011)
Total Funding	Approx. 70 m £ Till stage 5 (2011)	Approx. 34 m £ Till stage 4 (2013)	52.8 m \$ Till stage 4 (2011)	86 m AUD Till stage 4 (2011)	70 m AUD Till stage 4 (2014)
Amount in €	Approx. 64 m €	Approx. 41 m €	Approx. 38 m €	Approx. 58 m €	Approx. 47 m €
Estimated TRL (2014)	8	7	6–7	7	7–8
Comments on the development path	Redesign of the WEC at development phase 5	Redesign of the WEC at development phase 4	Redesign of the WEC at development phase 4	Redesign of the WEC at development phase 4	Redesign of the WEC at development phase 4
Reference	[26, 27]	[28]	[29–31]	[32, 33]	[34, 35]

It would have been great to be able to extend Table 4.7 with a TPL rating for each technology. However, these values and there underlying calculations and assumptions are rarely publically shared by developers.

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